Supplementary Information: Non-CO_2 forcing changes will likely decrease the remaining carbon budget for 1.5°C

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ABSTRACT

One key contribution to the wide range of 1.5°C carbon budgets among recent studies is the non-CO_2 climate forcing scenario uncertainty. Based on a partitioning of historical non-CO_2 forcing, we show that currently there is a net negative non-CO_2 forcing from fossil fuel combustion (FFC), and a net positive non-CO_2 climate forcing from land-use change (LUC) and agricultural activities. We perform a set of future simulations in which we prescribed a 1.5°C temperature stabilization trajectory, and diagnosed the resulting 1.5°C carbon budgets. Using the historical partitioning, we then prescribed adjusted non-CO_2 forcing scenarios consistent with our model's simulated decrease in FFC CO_2 emissions. We compared the diagnosed carbon budgets from these adjusted scenarios to those resulting from the default RCP scenario's non-CO_2 forcing, and to a scenario in which proportionality between future CO_2 and non-CO_2 forcing is assumed. We find a wide range of carbon budget estimates across scenarios, with the largest budget emerging from the scenario with assumed proportionality of CO_2 and non-CO_2 forcing. Furthermore, our adjusted-RCP scenarios produce carbon budgets that are smaller than the corresponding default RCP scenarios. Our results suggest that ambitious mitigation scenarios will likely be characterized by an increasing contribution of non-CO_2 forcing, and that an assumption of continued proportionality between CO_2 and non-CO_2 forcing would lead to an overestimate of the remaining carbon budget. Maintaining such proportionality under ambitious fossil fuel mitigation would require mitigation of non-CO_2 emissions at a rate that is substantially faster than found in the standard RCP scenarios.

Supplementary Section 1: Temperature trajectory for the threshold avoidance budgets

To obtain a so-called threshold or temperature avoidance budget for the $\Delta T=1.5°C$ target, we prescribed a surface air temperature trajectory, and ran the model in a mode, in which it diagnosed the necessary fossil fuel (FF) emission to reach this temperature target (Fig. 1).

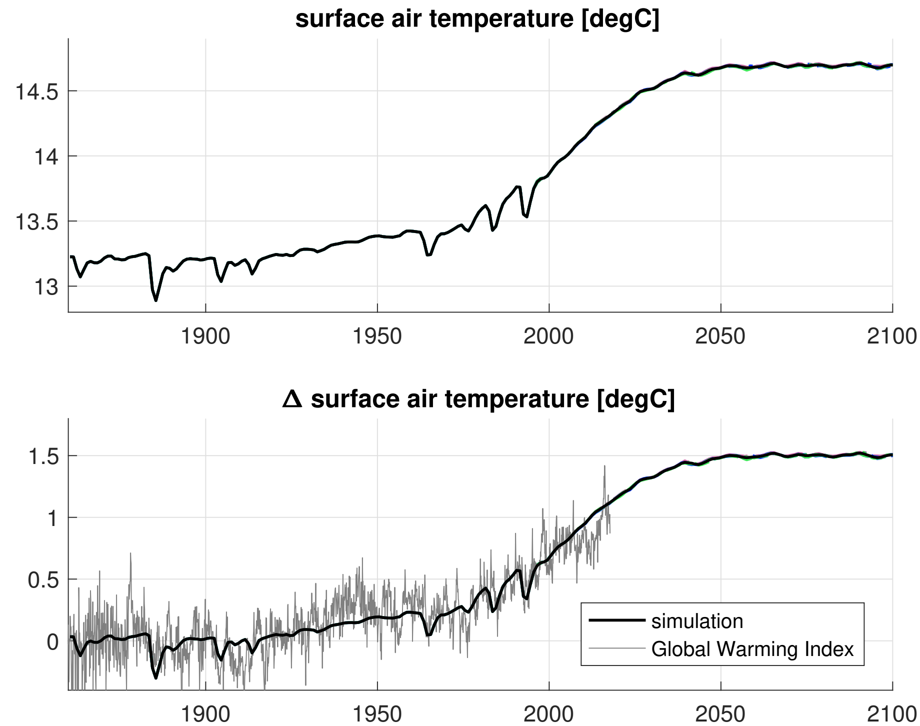

Figure 1. Temperature trajectory for the 1.5°C temperature change
top: Temperature output from the simulations **bottom**: as temperature anomaly from the 1850-1879 reference period. The Global Warming Index data referenced to the same pre-industrial period is shown for comparisons (grey line)[1].

Supplementary Section 2: Detailed description of the non-CO_2 forcing scenarios

In the following, we briefly describe the characteristics of each scenario (see also Table 1):

S1 - RCP8.5: The business-as-usual scenario (RCP8.5) shows the largest increase in the net non-CO_2 forcing. This scenario assumes continuing high LUC and FFC activity levels, and as a result, the non-CO_2 GHG forcing is increased by 0.71 W/m^2, and the LUC CO_2 emissions are increased by 212 GtCO_2. Similarly, the CO_2-fe emissions from LUC albedo changes are increased by 85 GtCO_2. And as with the RCP4.5, the aerosol forcing is assumed to be managed, and hence aerosol forcing decreases by 0.31 W/m^2. The net non-CO_2 forcing accordingly increases by 1.02 W/m^2 plus LUC effects in 2055 relative to the beginning of this scenario.

S2 - RCP4.5: The RCP4.5 forcing scenario assumes an increase in agricultural productivity and hence a reduction of agricultural land area, resulting in lower LUC CO_2 emissions than in RCP2.6, of 195 GtCO_2 from 2005 to 2055. In the same way, the negative CO_2-fe emissions from LUC albedo changes are only slightly increased by 50 GtCO_2. The non-CO_2 GHG forcing in this scenario first slightly increases but then reaches almost the same level of 0.06 W/m^2 lower in 2055 than in 2005. At the same time it is assumed that measures are take to reduced the atmospheric aerosol burden, and hence the aerosol forcing is decreased by 0.44 W/m^2. This results in an increase of the net non-CO_2 forcing of 0.50 W/m^2 plus LUC effects, relative to the beginning of the scenario.

S3 - RCP2.6: The RCP2.6 scenario assumes the implementation of bioenergy carbon capture and storage, which acts to increase LUC CO_2 emissions in 2050 by about 302 GtCO_2, relative to year 2005. Accordingly, the negative CO_2-fe emissions from LUC albedo changes also increases by 135 GtCO_2. The forcing from non-CO_2 GHGs slightly decreases by 0.21 W/m^2, while the negative forcing from aerosols is also reduced by 0.42 W/m^2. In total there is an increase in the net non-CO_2 forcing of 0.21 W/m^2 plus LUC effects in 2055, relative to the beginning of the scenario.

Sxb - RCP minus FFC: In addition to the default RCPs, we show scenarios in which non-CO_2 greenhouse gas and aerosol forcing associated with fossil fuel combustion (FFC) is reduced as diagnosed for the respective RCP scenario, while the forcing from agricultural, LUC and other human activities still follows the default RCP scenario. Given the partitioning of the different forcing agents from section 1 in the main article, we know that the FFC contribution to positive non-CO_2 GHGs is lower than for aerosols. Accordingly the radiative forcing from positive non-CO_2 forcing in the RCP2.6/4.5/8.5 scenario decreases by 0.46/0.27/-0.21 W/m^2, respectively, while the negative aerosol forcing decreases by 0.89/0.95/0.88 W/m^2 (Figure 1 of the main article). The net non-CO_2 forcing accordingly increases by 0.43/0.68/1.09 W/m^2 in the RCP2.6/4.5/8/5 minus FFC scenarios, respectively, relative to the beginning of the scenario in 2005.

S4 - CO_2 α net non-CO_2 : Lastly, we wanted to explore the impact of assuming proportionality between CO_2 induced forcing to net non-CO_2 forcing. This is an assumption, made by several recent studies[2,3], of a constant future ratio between the net non-CO_2 forcing and the CO_2 induced forcing. For this implementation we used the observed ratio of the net non-CO_2 forcing to the total CO_2 forcing for the twenty years period from 1995-2015, which gives a value of 0.26. Realizing that the total CO_2-fe budgets are the same for all the forcing scenarios, we inferred the CO_2 and non-CO_2 forcing equivalent emissions for this scenario as using the following equation: $E_{total} = E_{non-CO_2} + E_{CO_2} = (0.26 + 1) * E_{CO_2}$

Table 1. Non-CO_2 and CO_2 forcing in units of GtCO_2-fe and GtCO_2 at the point 1.5°C is reached relative to 2005 in the different scenarios. Values are given with a 1 GtCO_2 accuracy.

Scenario	non-CO_2 GHGs	aerosols	land-use albedo	total non-CO_2	LUC	FFC	total CO_2
S1 - RCP8.5	787	193	-72	908	212	56	268
S2 - RCP4.5	375	168	-44	499	177	485	662
S3 - RCP2.6	127	382	-110	399	281	448	729
S1b - RCP8.5 minus FFC	305	614	-80	839	194	37	231
S2b - RCP4.5 minus FFC	43	603	-55	591	155	320	475
S3b - RCP2.6 minus FFC	-113	636	-114	409	267	410	677
S4 - CO_2 α net non-CO_2	-	-	-	231	-	-	881

Supplementary Section 3: Scaling of non-CO_2 forcing agents according to their respective fossil fuel emissions scenarios

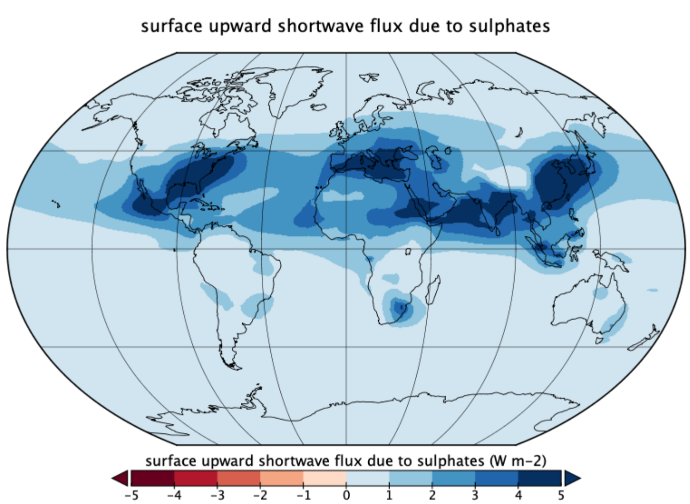

Figure 2. **Spatial distribution of 2005 aerosol radiative forcing in the UVic ESCM**

Radiative forcing from non-CO_2 GHGs are aggregated and implemented in the UVic ESCM through a change in the radiative transfer scheme[4]. To obtain sulphate aerosol forcing, SO_4 concentrations are vertically integrated to determine the atmospheric sulphate aerosol burden (g m^{-2}). The burden is then multiplied by a constant specific extinction cross-section factor of 8 m^2 g^{-1} to obtain the optical depth. The forcing from monthly resolved data is then calculated internally in the UVic ESCM from a change in surface albedo[4]. The spatial distribution of aerosol forcing as diagnosed by the UVic ESCM is shown in figure 2, and agrees well with the pattern from figure 13 in Stevens et al.[5]. In 2005, the UVic ESCM has a global mean radiative forcing from all aerosol effects of -1.12 W/m^2, which is within the range of uncertainty as given by the IPCC AR5[6]. A more detailed evaluation of the UVic ESCM's response to aerosol forcing can be found in Hienola et al.[7].

To obtain scenarios with a more consistent treatment of non-CO_2 emissions according to the diagnosed fossil fuel emissions for a 1.5 scenario (i.e., scenarios S1b, S2b and S3b), we use the partitioning of current non-CO_2 forcing into their respective sources (see table 1 for the main article). This percentage of the respective non-CO_2 forcing agent (shown in Figure 3) was then scaled down following the annual fossil emissions as diagnosed in the respective scenario, taking into account the different atmospheric lifetimes of the forcers. As such it becomes evident, that aerosols with shorter atmospheric lifetimes of days to a few years, show a more immediate reaction to reductions in fossil fuel emissions compared to, for example, methane radiative forcing, where methane has a lifetime of about a decade in the atmosphere[8,9]. For this analysis we used the lifetimes as given in the IPCC's AR5 WGI[6].

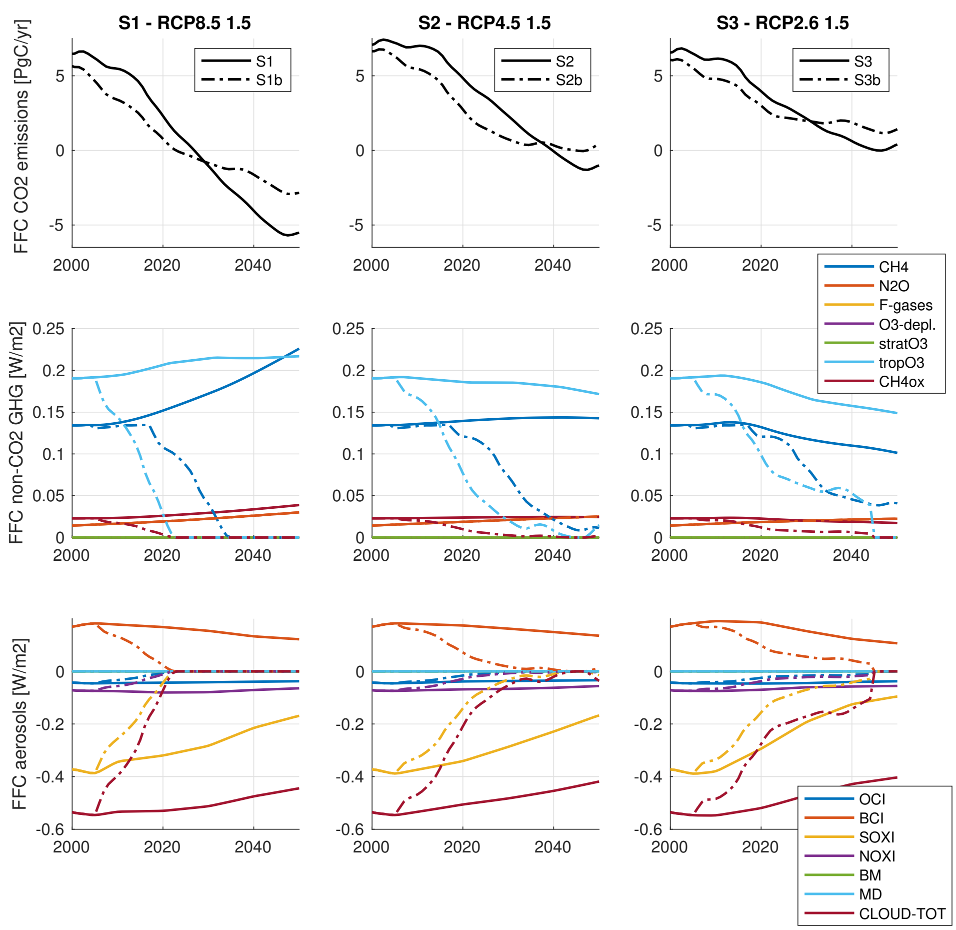

Figure 3. Scaling of non-CO_2 forcing agents according to their respective fossil fuel emissions scenarios
From left to right, the data for scenarios S1/S1b, S2/S2b and S3/S3b are shown. The first row shows the annual diagnosed fossil fuel emissions, the second row the radiative forcing from fossil fuel co-emitted non-CO_2 GHGs and the third row the radiative forcing from fossil fuel co-emitted aerosol and aerosol precursors.

Supplementary Section 4: Comparison of the forcing scenarios with the new Shared Socioeconomic Pathways (SSPs)

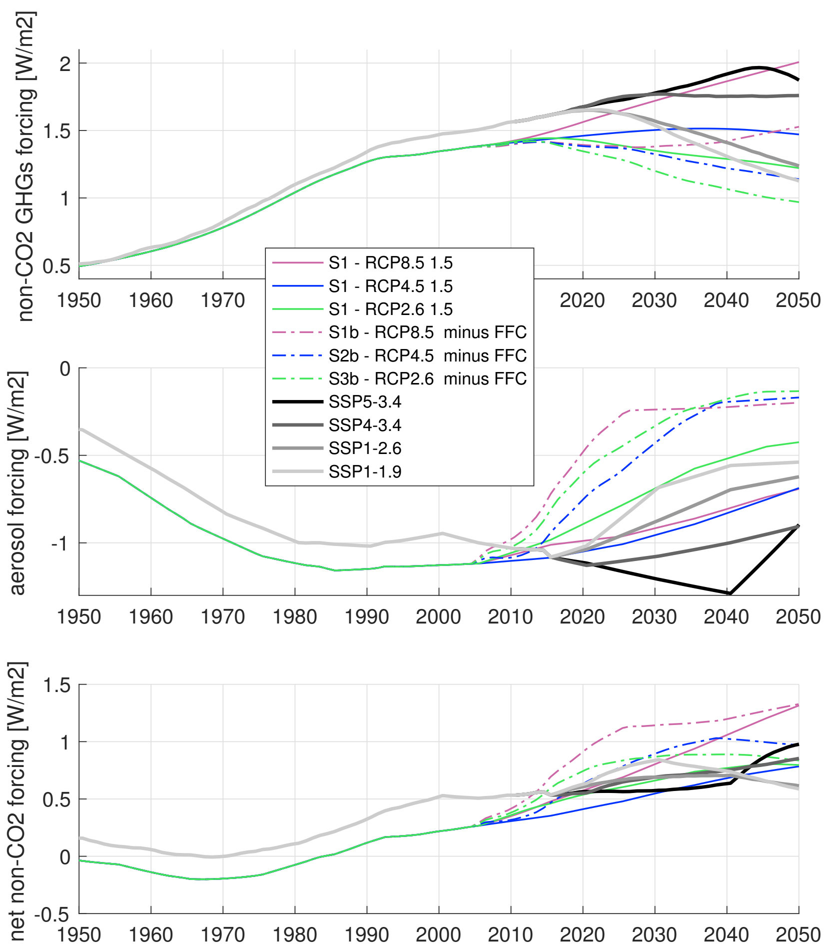

Figure 4. Comparison of the forcing scenarios with the Shared Socioeconomic Pathways (SSPs)
Scenarios as shown in figure 1 of the main text, set into the context of four of the newly published SSPs: SSP5 -3.4 is an overshoot scenario, SPP4-3.4 is a pathway with low challenges to mitigation and therefore is a plausible pairing with a relatively low forcing, SSP1-2.6 is the updated scenario for RPC2.6 - a 2°C scenario, and SSP-1-1.9 is the scenario which is meant to lead to a likely (> 66%) probability of staying below 1.5°C in 2100.

To set the scenarios presented in the main article into context, we compared them with the most ambitious of the newly published Shared Socioeconomic Pathways (SSPs), reaching between 3.4 and 1.9 W/m^2 by the end of the century (see Figure 4). The SPP1-1.9 is the only scenario with a likely (> 66%) probability of staying below 1.5°C in 2100. The other scenarios are closer to a 2°C goal: the SSP1-2.6 is the updated Representative Concentration Pathway 2.6 (RCP2.6), the SSP4-3.4 is at the low range of the future forcing pathways, and SSP5-3.4 is a temperature overshoot scenario, in which unmitigated climate change occurs through 2040, at which point aggressive mitigation is undertaken to rapidly reduce emissions to zero by about 2070 and to net negative levels thereafter.
To allow for an appropriate comparison, especially for the aerosol forcing, we applied mostly the same methodologies as for obtaining the RCP data sets. The only exception being that we updated the forcing equations for CO2, CH4 and N2O, for which we now follow the formulations from Etminan et al.[10]. As a result the new data shows a slightly higher total non-CO2 GHG forcing by the start of the SSP scenarios in 2010. The global mean aerosol forcing in the SSPs is about 0.1 W/m^2 lower throughout the historical period compared to the RCP forcing, but reaches very similar level by 2010. Note, that the SSP aerosol

forcing was been adjusted within the range of estimate uncertainties to match the historical temperature trajectory. Overall the net non-CO2 forcing is accordingly substantially higher in the SSP throughout the historical period, and by about 0.22 W/m^2 in 2010.

The scenarios for the forcing of non-CO2 GHGs are in good agreement to the forcing levels reached in the SSPs in 2050. Only the S1 - RCP8.5 and the S3b - RCP2.6 minus FFC scenarios, with 2 W/m^2 and 0.97 W/m^2 in 2050, respectively, are slightly outside of the forcing range of the four SSPs (1.13 to 1.89 W/m^2). Note, that the total increase in non-CO2 GHG forcing in the RCPs is still higher compared to the SSP, since their level in 2010 was lower to begin with. In contrast, the aerosol forcing in the most ambitious SSP, SSP1-1.9, only goes down to -0.54 W/m^2, which is an even higher level compared to the default RCP2.6. Accordingly, the Sxb scenarios with values between -0.13 and -0.2 W/m^2 in 2050, all lie outside of the projected SSP aerosol forcing.

The higher increase in non-CO2 GHGs radiative forcing and the higher decrease in the aerosol forcing in the RCPs compared to the SSPs lead to an overall higher increase in non-CO2 forcing compared to the SSP between 2010 and 2040, especially for the adjusted RCPs. However, the levels of total non-CO2 forcing in the RCPs in 2050 are within the range of the SSPs, with the exception of the S1 and S1b scenario, which we accordingly label as less likely in the main text.

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